Neutrino Physics with Large Underground Detectors

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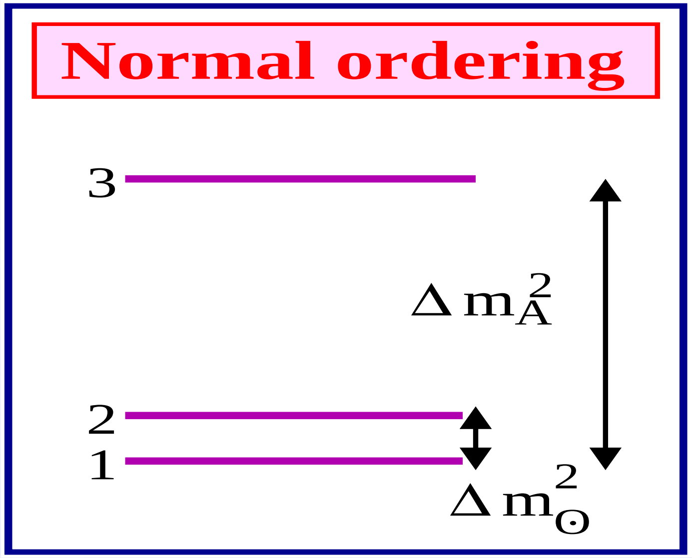
1 – Present status

Neutrino oscillations are crucial in our understanding of neutrino physics as they imply that

NEUTRINOS ARE MASSIVE AND THEY MIX.

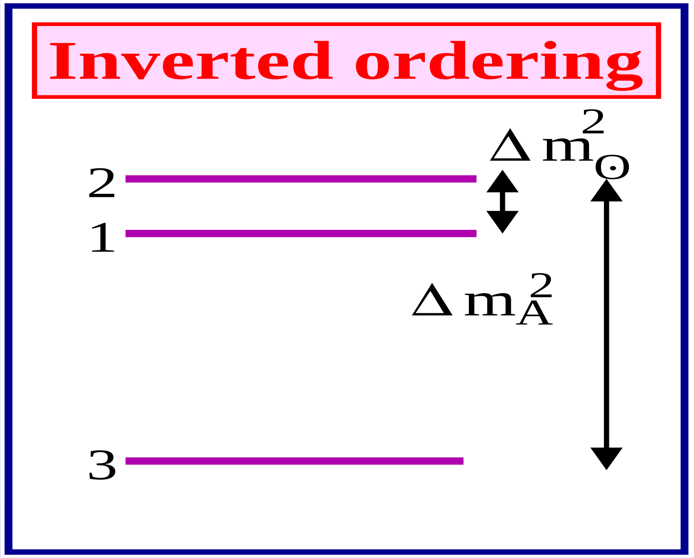
The explanation of neutrino masses requires physics beyond the Standard Model.

1 – Present status



Normal ordering

$$m_1 = m_{\rm MIN}$$
$$m_2 = \sqrt{{m_{\rm MIN}}^2 + \Delta m^2_\odot}$$
$$m_3 = \sqrt{{m_{\rm MIN}}^2 + \Delta m^2_{\rm atm}}$$



Inverted ordering

$$m_3 = m_{\rm MIN}$$
$$m_1 = \sqrt{{m_{\rm MIN}}^2 + \Delta m^2_{\rm atm} - \Delta m^2_\odot}$$
$$m_2 = \sqrt{{m_{\rm MIN}}^2 + \Delta m^2_{\rm atm}}$$

Measuring neutrino masses requires to know:

- $m_{\rm MIN}$
- sign(Δm^2_{31}).

Mixing is described by a unitary matrix:

$$|\nu_l\rangle = \sum_i U_{li}|\nu_i\rangle$$

U is the Pontecorvo-Maki-Nakagawa-Sakata matrix.

$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

Solar, reactor $\theta_\odot \sim 30^o$ **Atm, Acc.** $\theta_A \sim 45^o$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{-i\alpha_{31}/2+i\delta} \end{pmatrix}$$

CPV phase **Reactor, Acc.** $\theta < 12^o$ **CPV Majorana phases**

If $U \neq U^*$, there is leptonic CP-violation.

$$\boxed{P(\nu_l \to \nu_{l'}) \neq P(\bar{\nu}_l \to \bar{\nu}_{l'})}$$

- Establishing leptonic CP-V is a fundamental and challenging task.

- There are:

1 Dirac phase (measurable in long base-line experiments)

and 2 Majorana phases (one might be determined in neutrinoless double beta decay).

- Leptogenesis takes place in the context of see-saw models, which explain the origin of neutrino masses.

The observation of neutrinoless double beta decay (L violation) and of CPV in the lepton sector would be an indication, even if not a proof, of leptogenesis as the explanation for the observed baryon asymmetry of the Universe.

Questions for the future

- **What is the nature of neutrinos**?

Whether they Majorana ($\nu = \bar{\nu}$) or Dirac ($\nu \neq \bar{\nu}$). Majorana neutrinos violate the lepton number.

- **Absolute value of neutrino masses**?

Needed the type of hierarchy and the mass scale of the lightest neutrino.

- **Leptonic CP-violation**?

$\delta \neq 0, \pi$ and/or $\alpha_{ij} \neq 0, \pi$.

- **Standard scenario**?

NSI, sterile neutrinos, violations of unitarity

A wide-experimental program is addressing these questions.

2 – Study of neutrino properties with Megaton-scale detectors

Large underground detectors allow to determine neutrino properties, by studying

- Solar neutrinos
- Atmospheric neutrinos
- Supernova neutrinos
- **Long baseline oscillations**: WC and Liquid Argon detectors can be used for superbeams, betabeams and neutrino factory (LiAr, iron or scintillator calorimeters with magnetisation) .

3 – Long baseline neutrino experiments

Long baseline neutrino experiments search for the subdominant $\nu_{\mu,e} \longrightarrow \nu_{e,\mu}$ and $\bar{\nu}_{\mu,e} \longrightarrow \bar{\nu}_{e,\mu}$ appearance:

$$\boxed{P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E}}$$

for negligible matter effects and CPV.

- **Type of mass hierarchy**: **LBL oscillations**
- **Leptonic CP-violation**? **LBL oscillations**
- **Tests of standard 3-neutrino scenarios**: **LBL oscillations**

- Matter effects: These oscillations take place in matter (Earth), (e^-, p and n). A potential V in the Hamiltonian ($V = \sqrt{2}G_F(N_e - N_n/2)$) describes matter effects.

The probability can be approximated as (for no CPV):

$$\boxed{P_{\nu_\mu \to \nu_e} = \sin^2\theta_{23}\sin^2 2\theta_{13}^m \sin^2\frac{\Delta_{13}^m L}{2}}$$

The mixing angle changes with respect to the vacuum case:

$$\boxed{\sin 2\theta_m = \frac{(\Delta m^2/2E)\sin 2\theta}{\sqrt{\left(\frac{\Delta m^2}{2E}\sin 2\theta\right)^2 + \left(\frac{\Delta m^2}{2E}\cos 2\theta - V\right)^2}}}$$

- CPV: A measure of CP- violating effects is provided by:

$$\boxed{A_{CP} = \frac{P(\nu_l \to \nu_{l'}) - P(\bar{\nu}_l \to \bar{\nu}_{l'})}{P(\nu_l \to \nu_{l'}) + P(\bar{\nu}_l \to \bar{\nu}_{l'})} \propto J_{CP} \propto \sin\theta_{13}\sin\delta}$$

The determination of δ and of the type of hierarchy is made more difficult by the presence of degeneracies, i.e. different sets of parameters which provide an equally good fit to the data. For ex.:

- (θ_{13}, δ) degeneracy [Koike, Ota, Sato; Burguet-Castell et al.] :

$$\begin{aligned} \delta' &= \pi - \delta \\ \theta'_{13} &= \theta_{13} + \cos\delta \sin 2\theta_{12} \frac{\Delta m^2_{12} L}{4E} \cot\theta_{23} \cot \frac{\Delta m^2_{13} L}{4E} \end{aligned}$$

Both (δ, θ_{13}) and (δ', θ'_{13}) give the same probability for neutrino and antineutrino oscillations, at fixed L and E.

Various strategies have been studied to resolve this problem and to achieve a good sensitivity to the unknown neutrino parameters.

4 – Synergy between Megaton detectors and long baseline oscillations

- Desirable characteristics for a long baseline experiment:

a) baseline > 800–1000 Km for significant matter effects

b) this implies a small flux and a very large (megaton scale) detector

c) detector with low energy threshold (100s of MeV) to fully exploit the oscillatory pattern of the signal (necessary for degeneracy resolution)

The synergy between LAGUNA-LBNO and LBL experiments is two-fold:

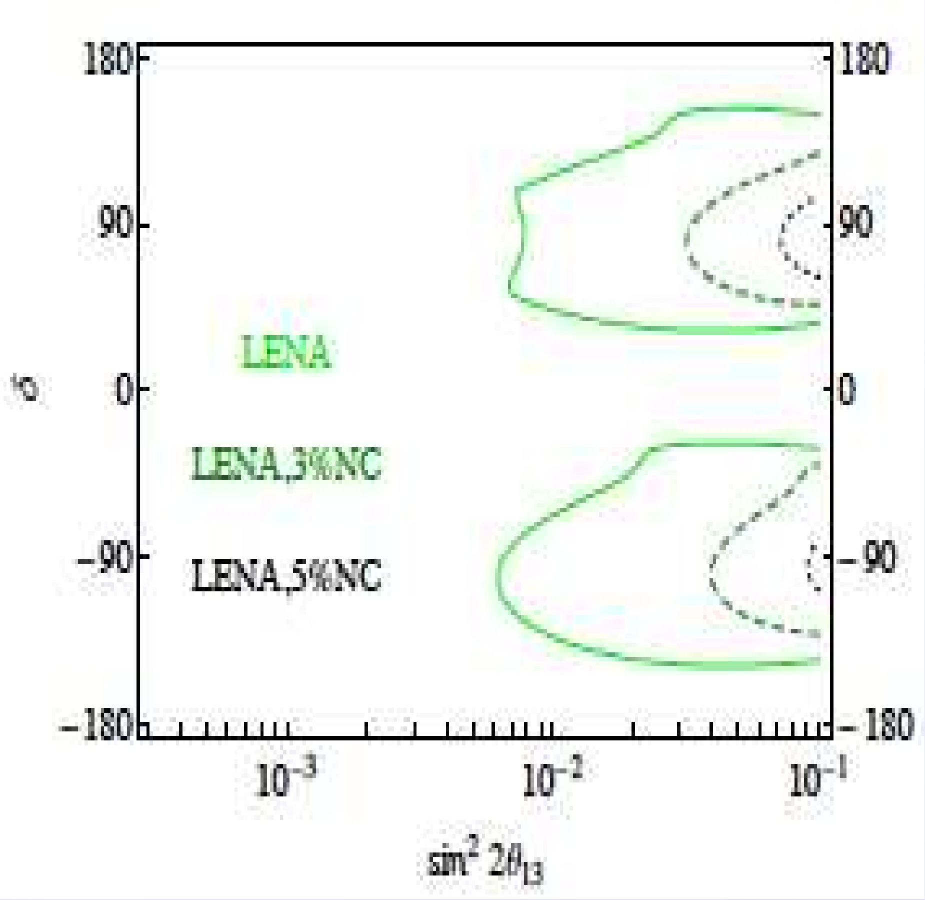
- **detectors**
- **location of the underground laboratory which defines the baseline.**

Detector

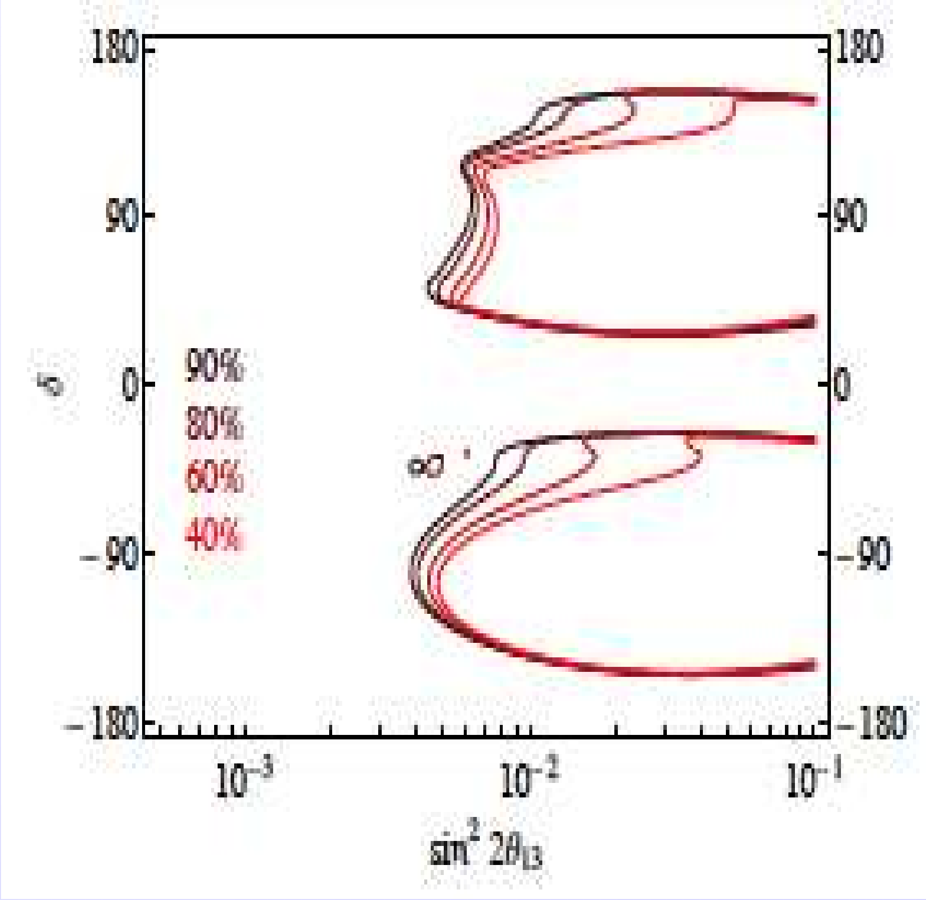
- The sensitivity of these experiments depends very much on the properties of the detector (backgrounds, energy resolution, size). It is critical to perform detailed simulations of these detectors.

- Superbeams and betabeams do not need magnetisation which is instead necessary for neutrino factory.
- The energy resolution and the threshold determine the ability to exploit the rich oscillatory pattern and therefore resolve degeneracies.
- The size and efficiency determine the statistics which can be reached, this is very critical for betabeams.
- Systematics errors might be the future limiting factors.

Impact on NC

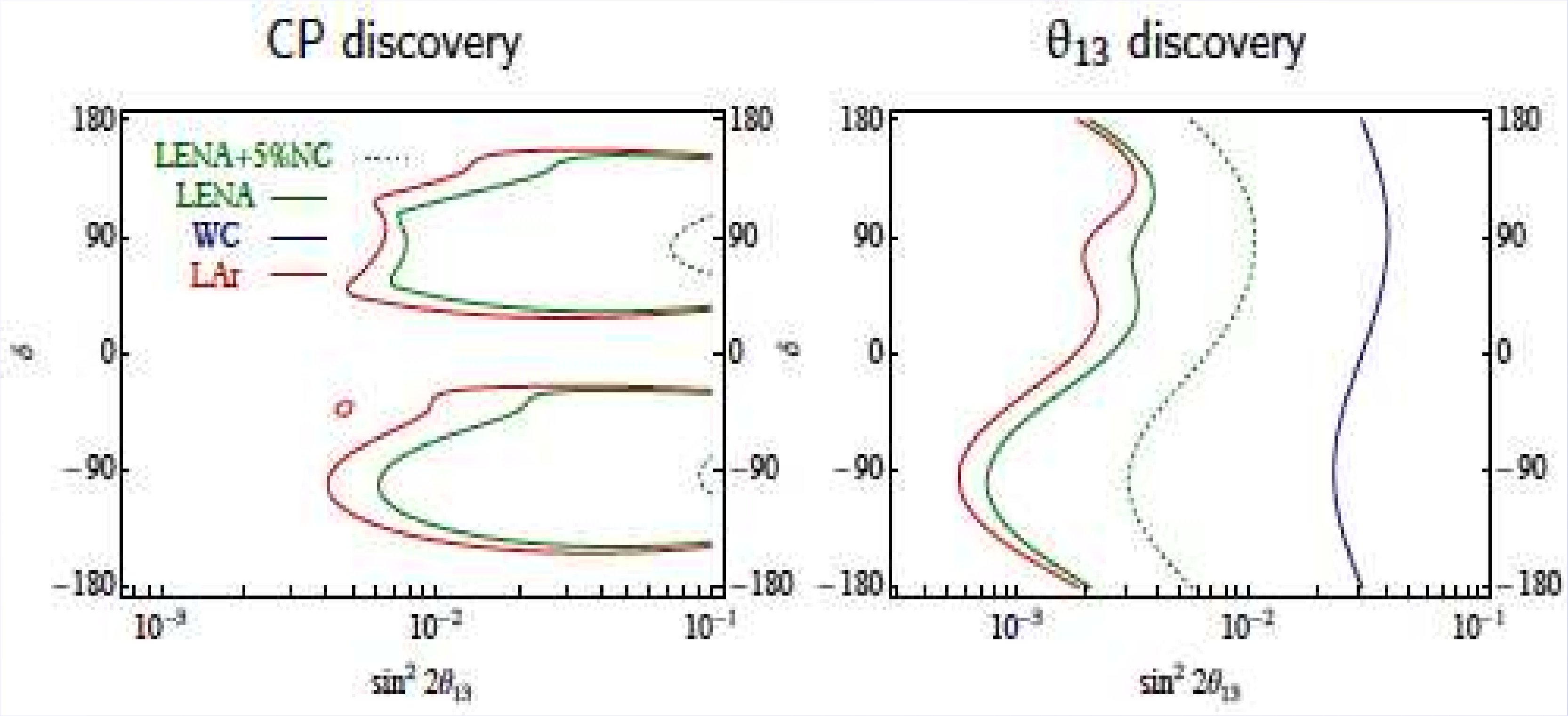


Quasi-elastic events



[Coloma, Li, SP]

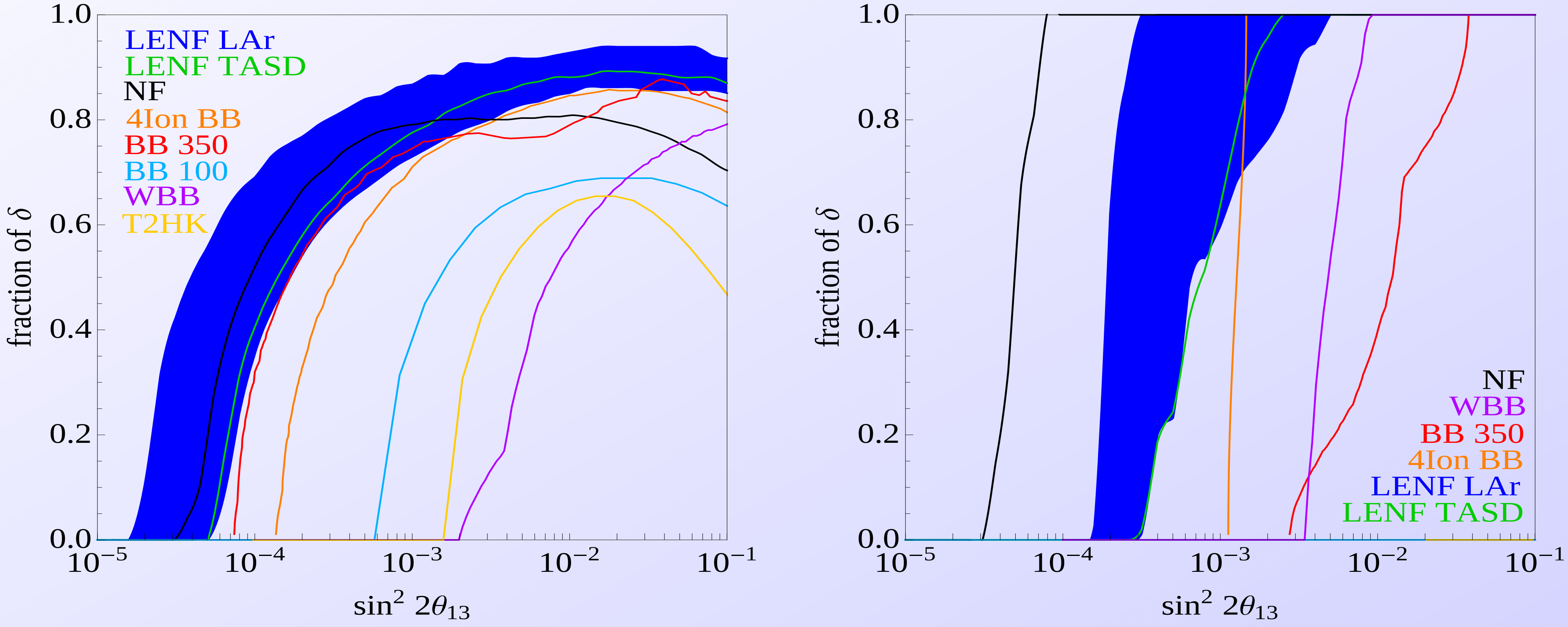
Sensitivity to CPV and θ_{13} for the CERN to Phyasalmi baseline, with LENA, MEMPHYS and GLACIER.



[Coloma, Li, SP]

5 – Future opportunities

Neutrino factories: ν_μ-ν_e beam from high-γ muons (4 GeV - 50 GeV).



Sensitivity to the CPV and type of neutrino mass hierarchy [Bross et al.]

A low energy neutrino factory has excellent sensitivity but requires a low threshold magnetised detector (LiAr, TASD or MIND).

6 – Conclusions

Megaton scale detectors have a wide physics reach.

- Studies of solar and atmospheric, reactor and geo-neutrinos as well as detection of supernova neutrinos (from a future SN and for the diffuse SN neutrino background).

- Long baseline neutrino oscillations. Superbeams and betabeams need Megaton-scale detectors (MEMPHYS, GLACIER, LENA). A LENF requires a magnetised detector.

- The choice and size of the detector combined with the baseline (determined by the location of the underground laboratory) is critical in defining the sensitivity of the experiment.

- **Detailed simulations of these detectors are needed to reliably determine efficiency, backgrounds, energy resolution, systematic errors.**